

Electronic Structure Studies of Undoped and Doped Cuprates Using High-Energy Spectroscopy

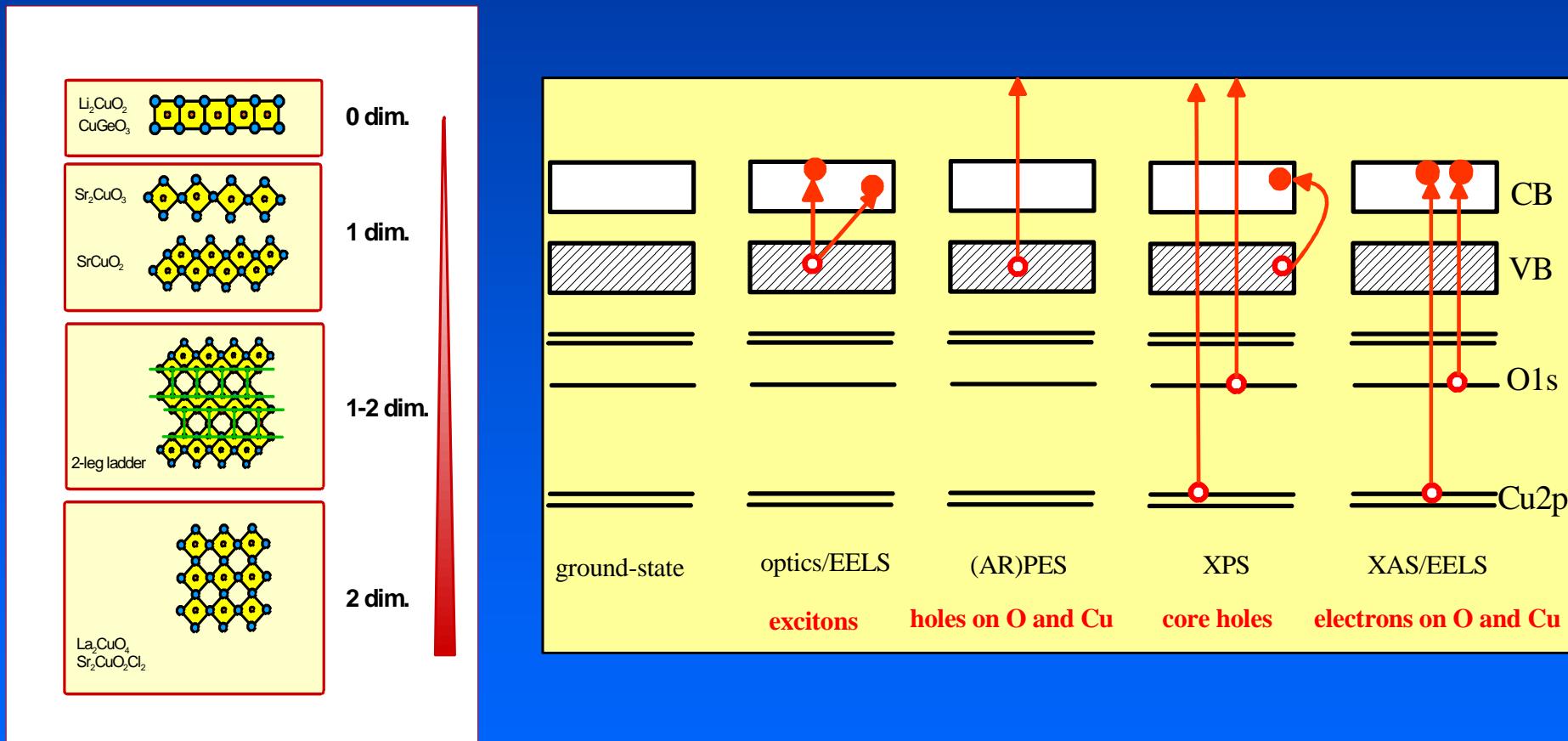
Jörg Fink

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and
TU Dresden**

Outline:

- **Introduction**
- **Fermi surface, bandstructure of bare particles,**
- **dressing of the charge carriers at the nodal and antinodal point**
- **circulating currents in the pseudogap range?**

Cuprates and High-Energy Spectroscopies

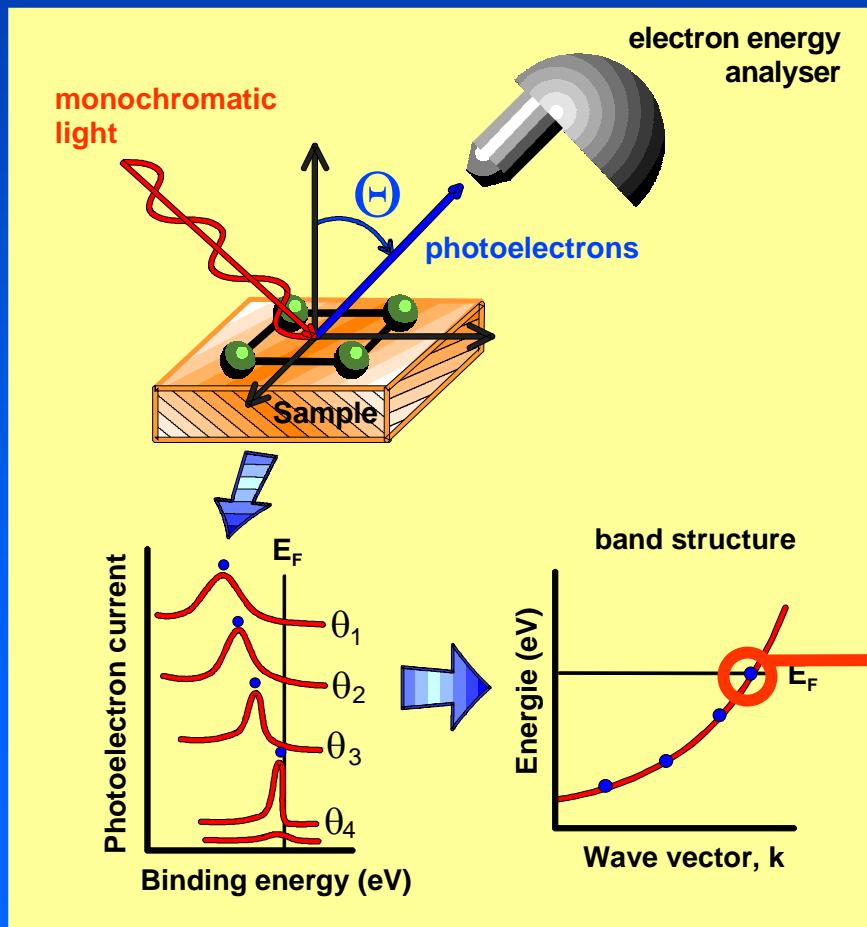


Angle-resolved photoemission (ARPES)

BESSY U125/1-PGM
ELETTRA
Gammadata He-lamp

SES 100
SES 200

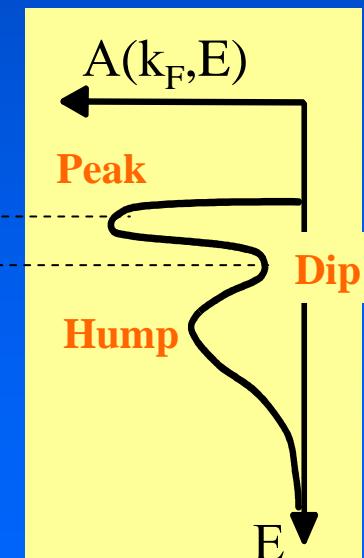
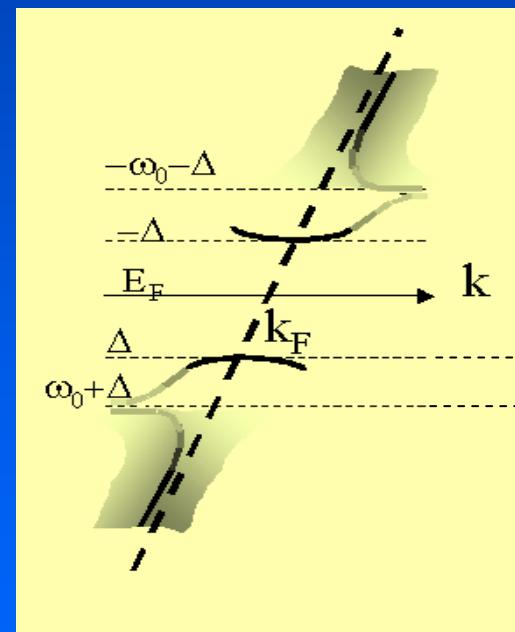
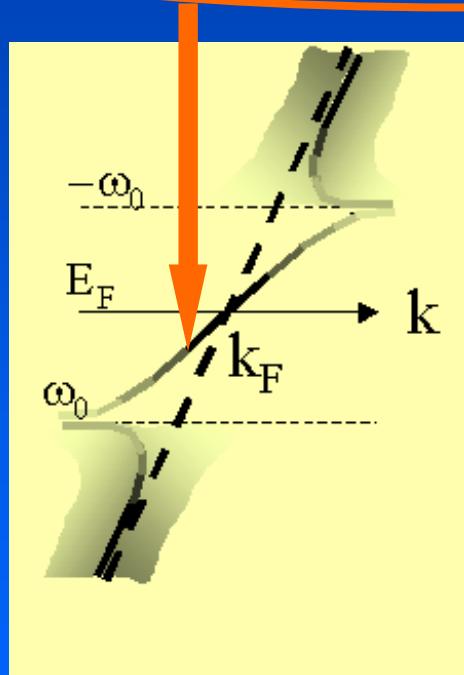
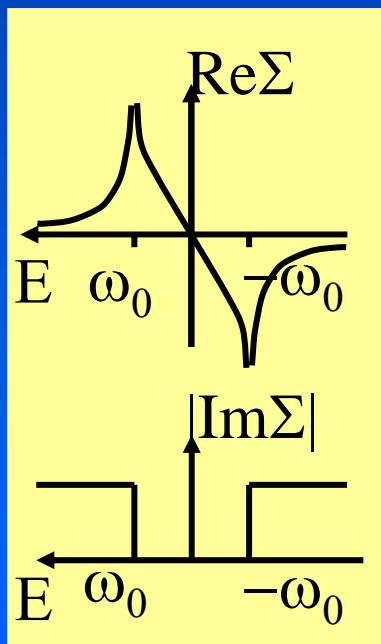
$\Delta E_{\text{tot}} = 8\text{-}25 \text{ meV}$
 $\Delta\Theta = 0.1\text{-}0.7^\circ$, $T_{\text{sample}} = 30\text{-}300 \text{ K}$



Dressing of charge carriers

Coupling to a single mode (phonons, spin fluct.)

$$m^* = (1 + \lambda)m \quad \lambda = -\delta \text{Re}\Sigma / \delta E|_{EF} \quad Z = 1/(1 + \lambda)$$

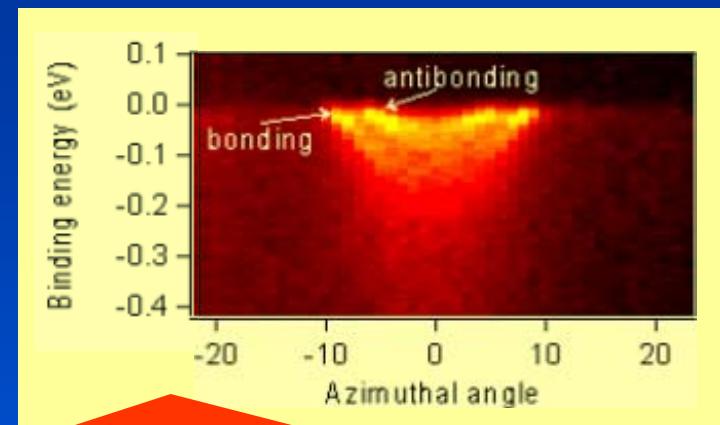
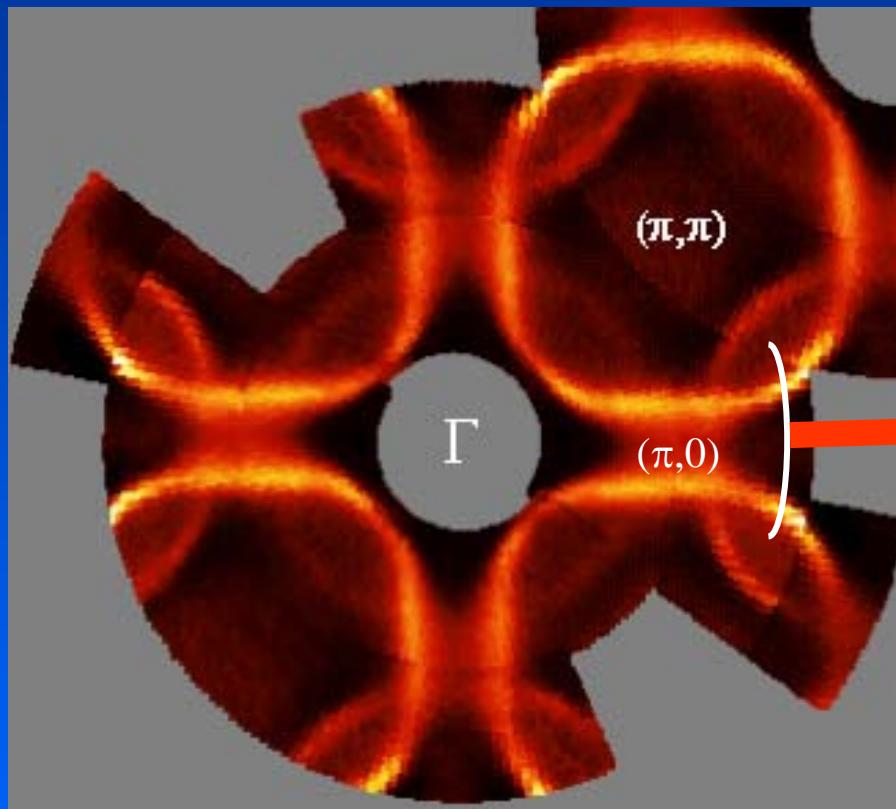


Engelsberg and Schrieffer, PR 131, 993(1963)

Scalapino in 'Parks' (1969)

Fermi surface of $\text{Bi}(\text{Pb})_2\text{Sr}_2\text{Ca}\text{Cu}_2\text{O}_{8+\delta}$

$h\nu = 21.2 \text{ eV}$



$h\nu = 25 \text{ eV}$

Kordyuk et al. Phys. Rev. B 66, 014502(2002)
Kordyuk et al. Phys. Rev. B 67, 064504 (2003)

How to get the bare-particle bandstructure?

- Assumption: $\Sigma(k_F, E_F)$ small or zero.

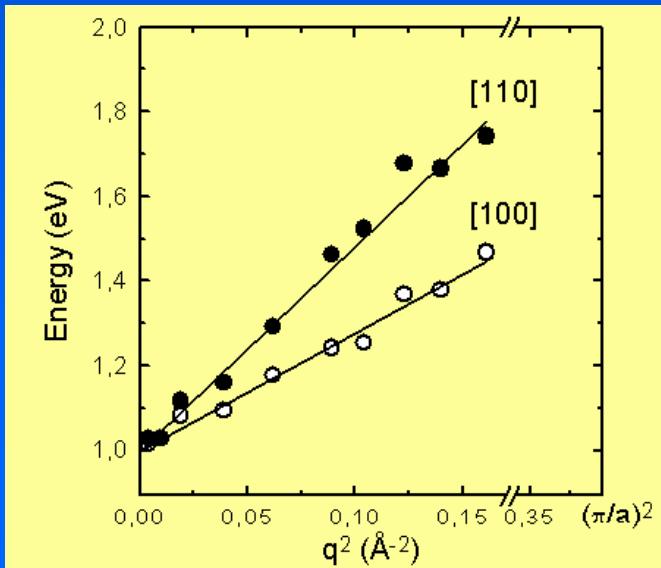
Fit of the Fermi surface by a TB bandstructure:

$$E_0(k)_{a,b} = \Delta\varepsilon - 2t[\cos(k_x a) + \cos(k_y a)] + 4t' \cos(k_x a) \cos(k_y a) - 2t'' [\cos(2k_x a) + \cos(2k_y a)] \pm t_\perp [\cos(k_x a) - \cos(k_y a)]^2 / 4$$

$$\Rightarrow t'/t \quad t''/t \quad t_\perp/t$$

t from $\text{Im}\Sigma$ along the nodal direction
 $\Rightarrow \text{KKA} \Rightarrow \text{Re}\Sigma \Rightarrow E(k) - \text{Re}\Sigma = E_0(k)$

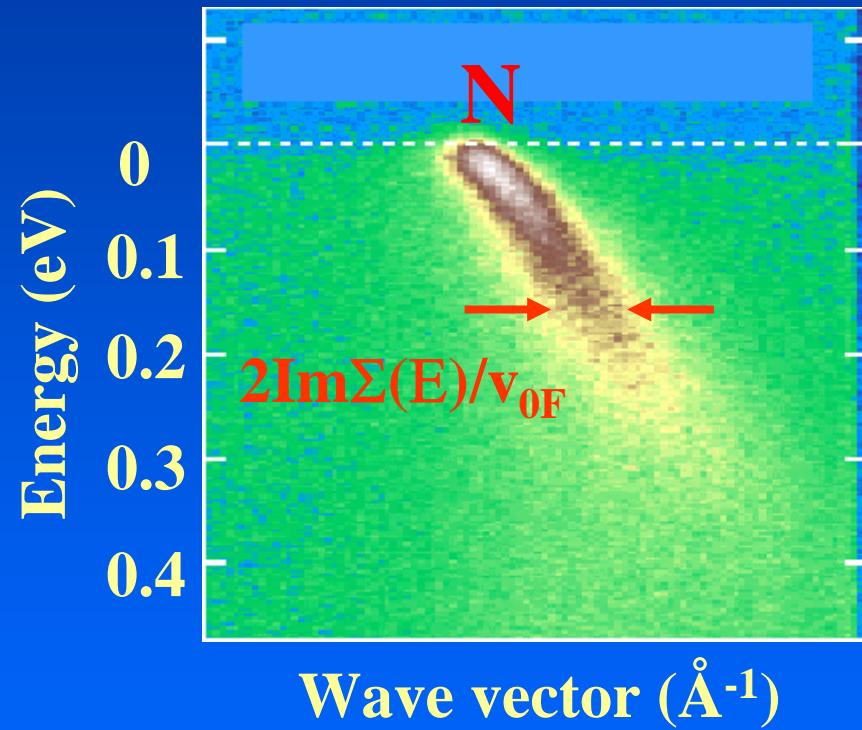
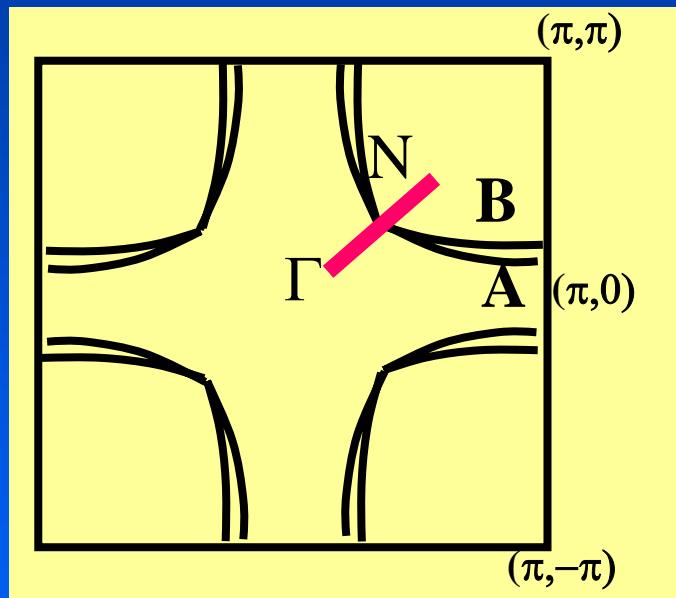
- From LDA bandstructure calculations



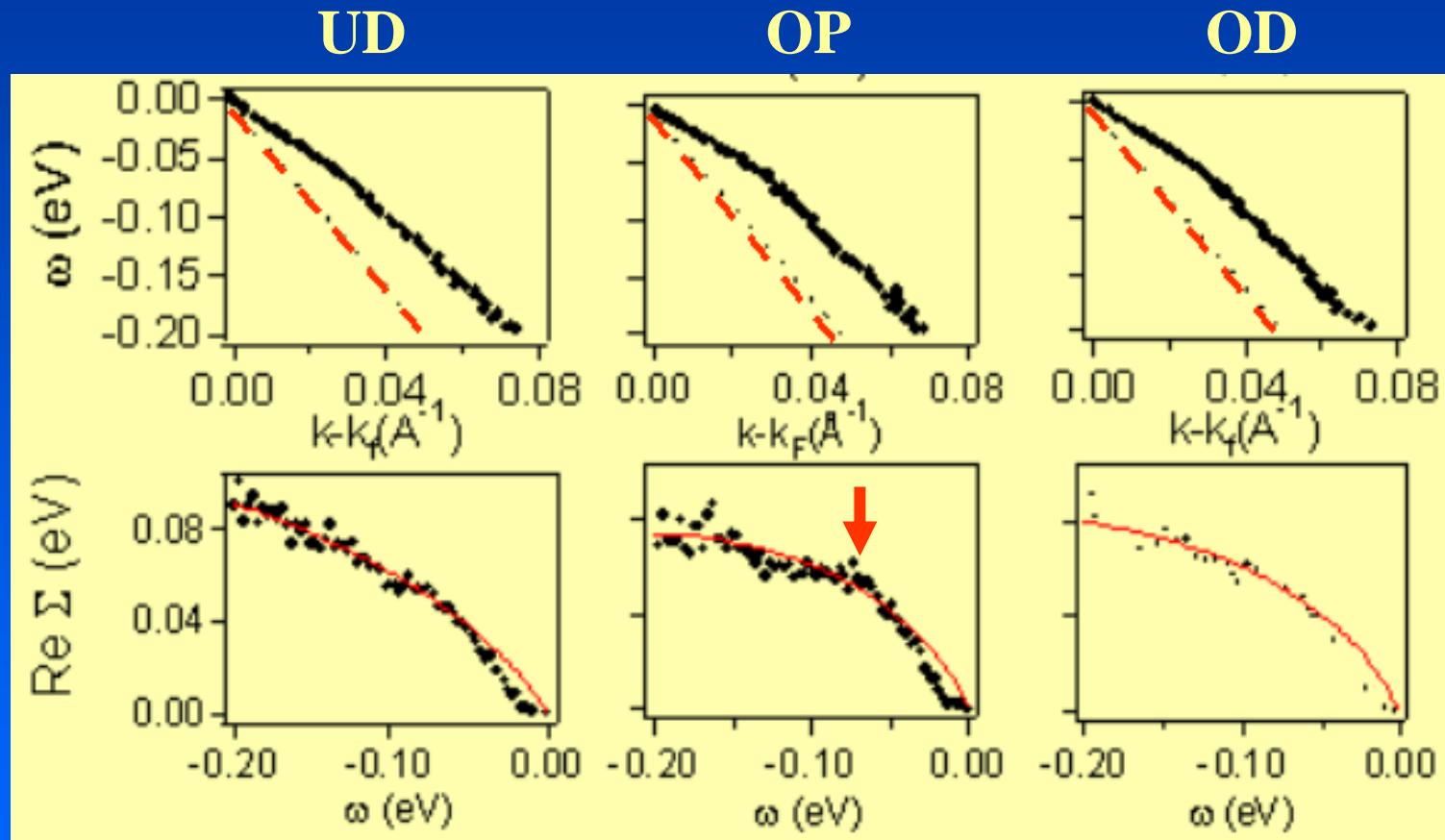
- By fitting the plasmon dispersion (from EELS). Measures averaged unrenormalized Fermi velocity.

Nücker et al. PRB 44, 7155 (1991);
Grigorian et al. PRB 60, 1340 (1999)

Dispersion in Pb-Bi-2212 along the nodal direction



Doping dependence of the mass enhancement at T = 30 K.



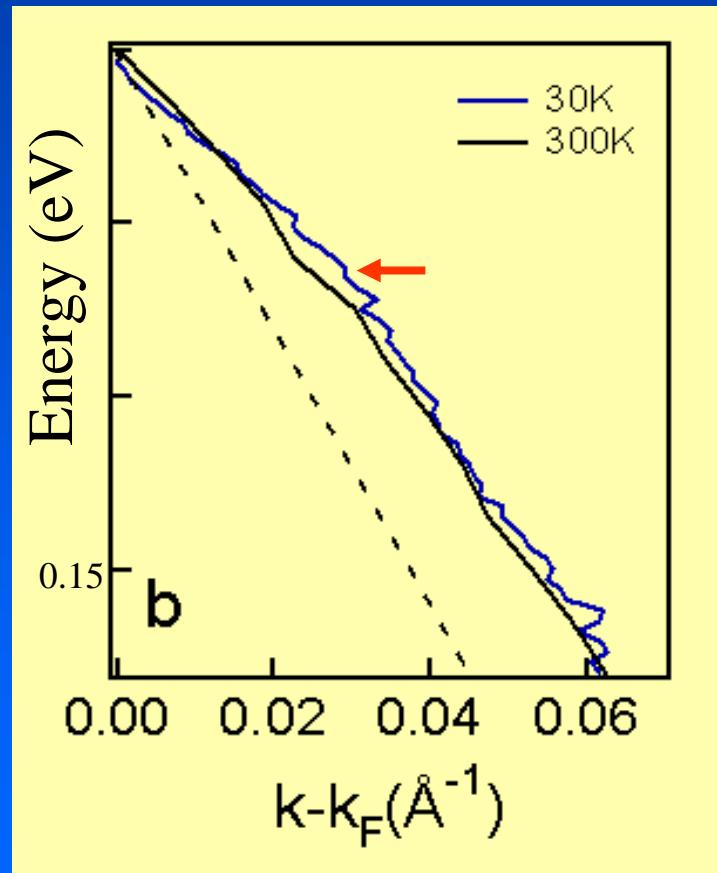
$$\text{Re}\Sigma(E) = \lambda'E \log(x/\omega_c) \quad x = (E^2 + \pi^2 T^2)^{1/2}$$

Close to marginal
Fermi liquid

$$\lambda(\neq f(x)) \sim 1$$

$$m^*/m \sim 2$$

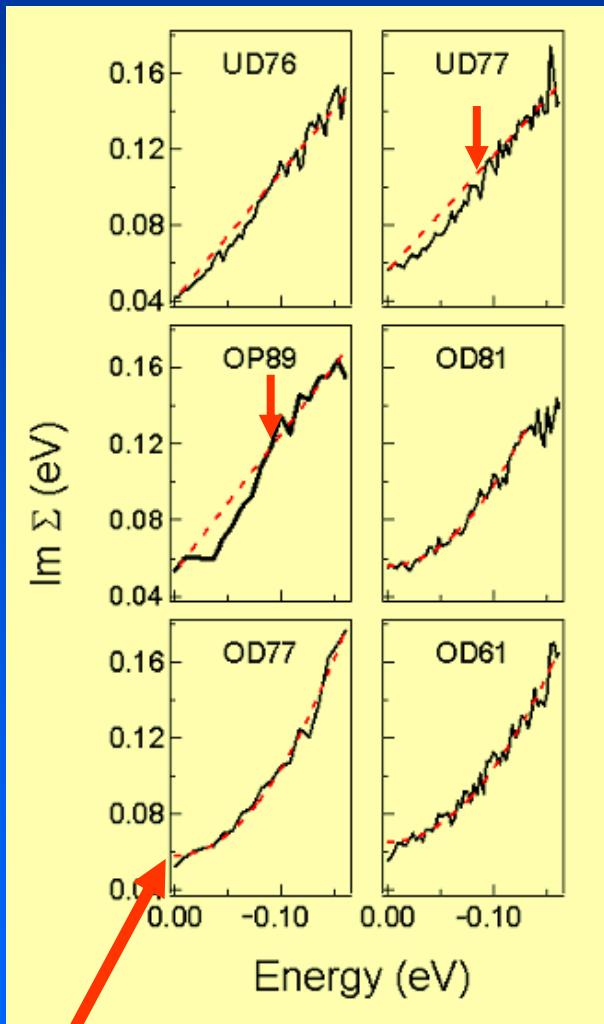
Temperature dependence



Very small additional renormalization below T_c near 70 meV.

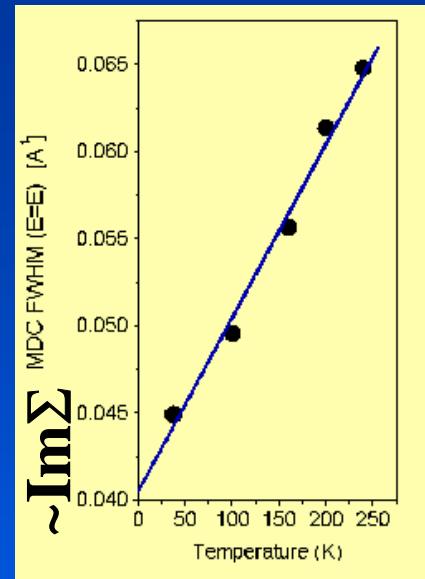
Doping dependence of the scattering rate

T= 30 K



Offset due to Δk and Σ_{imp}

UD



UD: almost linear in E and T. Marginal Fermi liquid behavior.

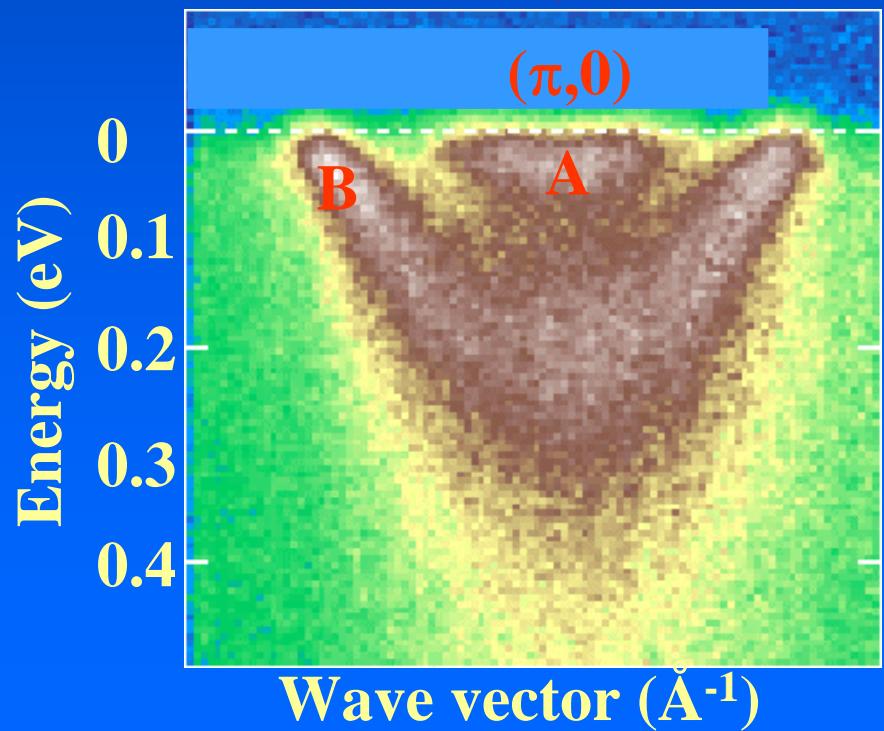
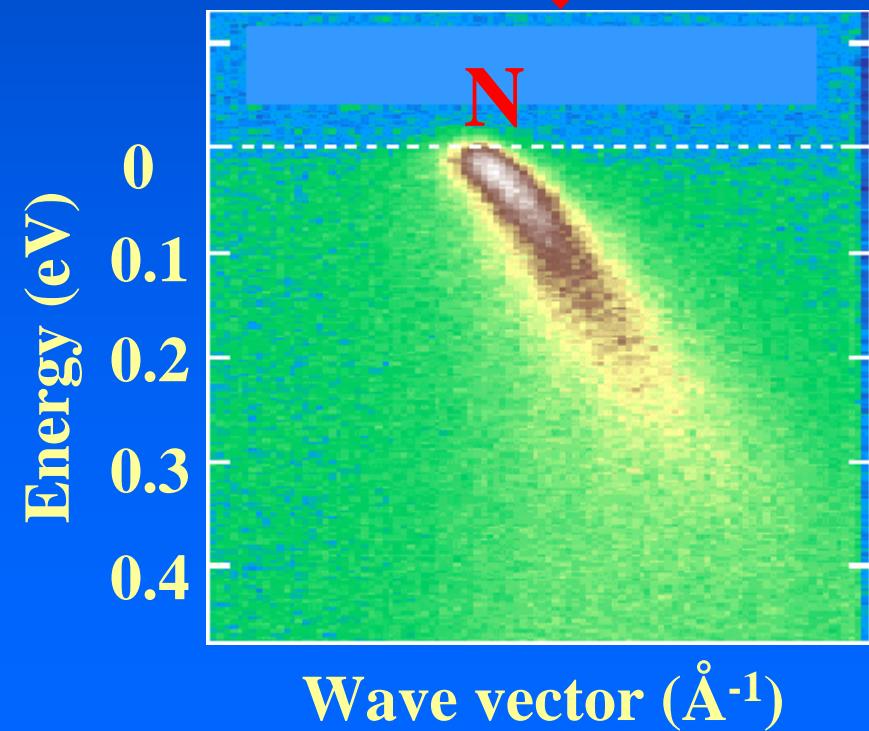
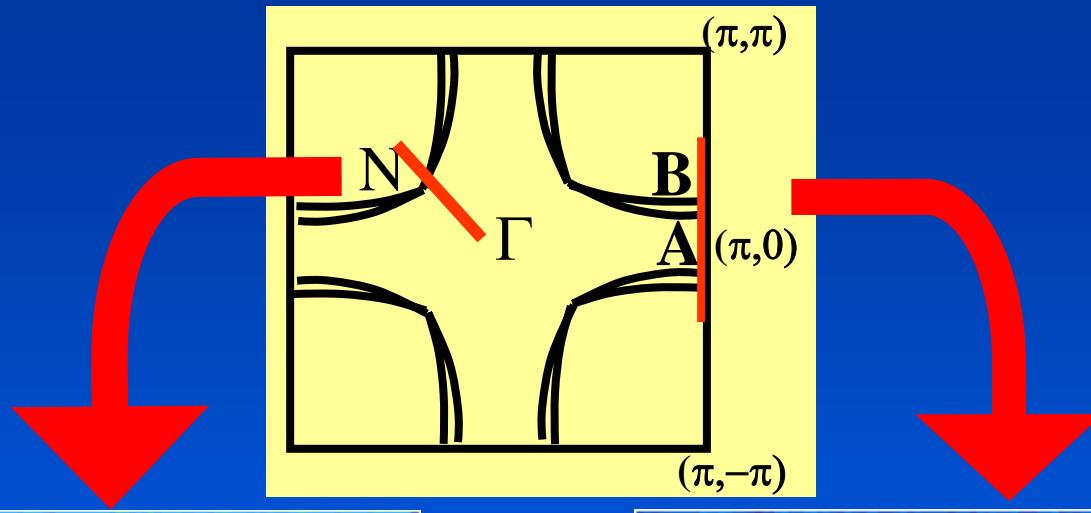
$$\text{Im}\Sigma(k_F, E) \sim [\alpha(kT)^2 + \beta E^2]^{1/2}$$

OD: quadratic in E, Fermi liquid behavior.

Summary on the results at the nodal point

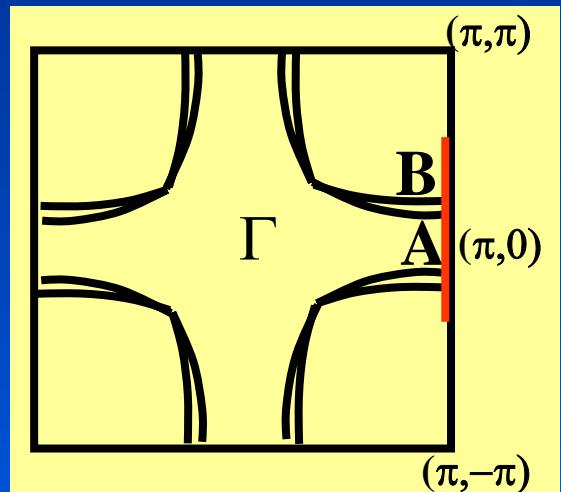
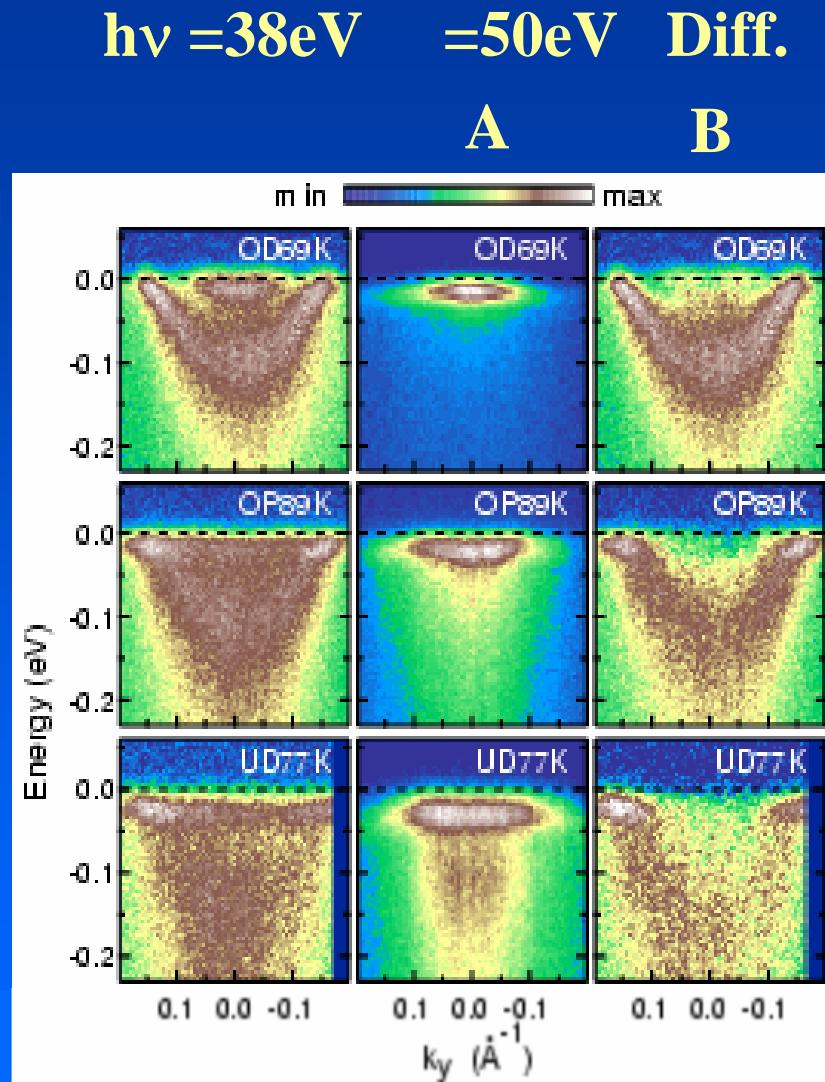
- strong renormalization over a large energy range ($E > 200\text{meV}$)
- coupling to a continuum
- at E_F : coupling constant $\lambda \sim 1$, effective mass ~ 2
- below T_c : very small additional renormalization at 70 meV.
Gap energy: 30 meV \Rightarrow coupling to a mode at ~ 40 meV
- UD: MFL \Rightarrow OD: FL

Going from the nodal to the anti-nodal point



Kink along the $(\pi,0)$ - (π,π) direction, $T = 30$ K $< T_c$

OD
OP
UD



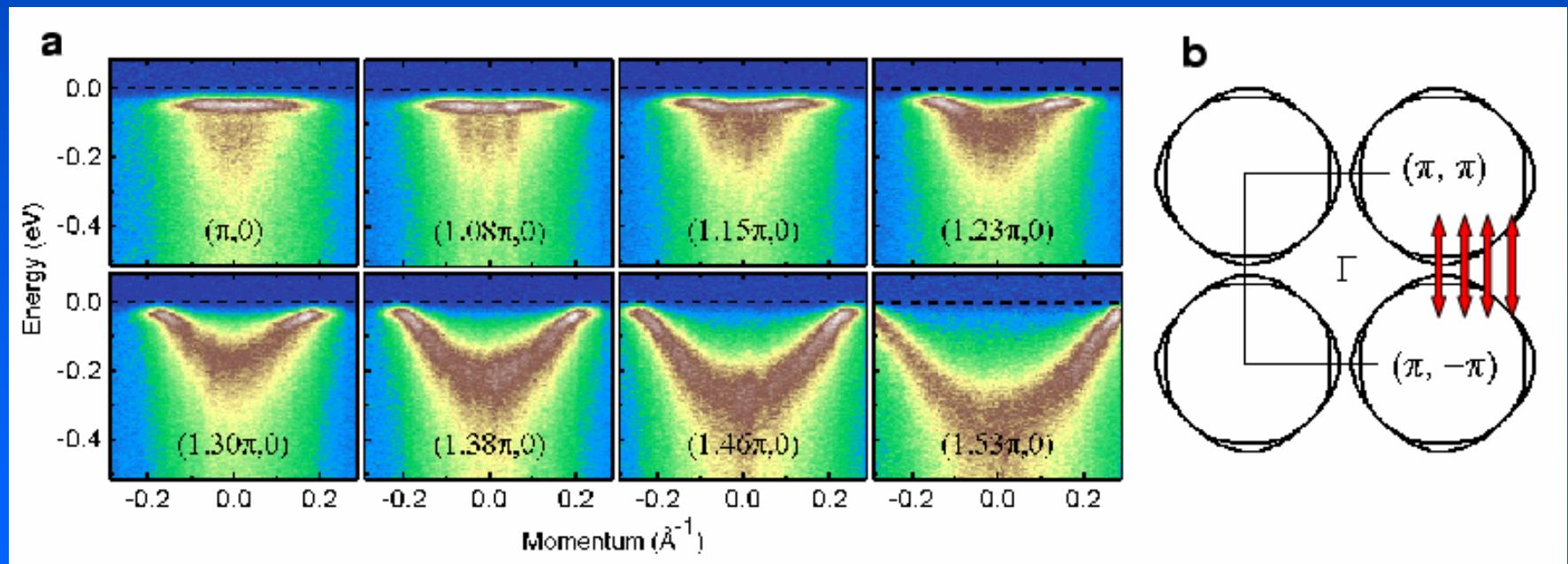
Kink at ~ 70 meV.

Kink increases strongly
with decreasing
dopant concentration

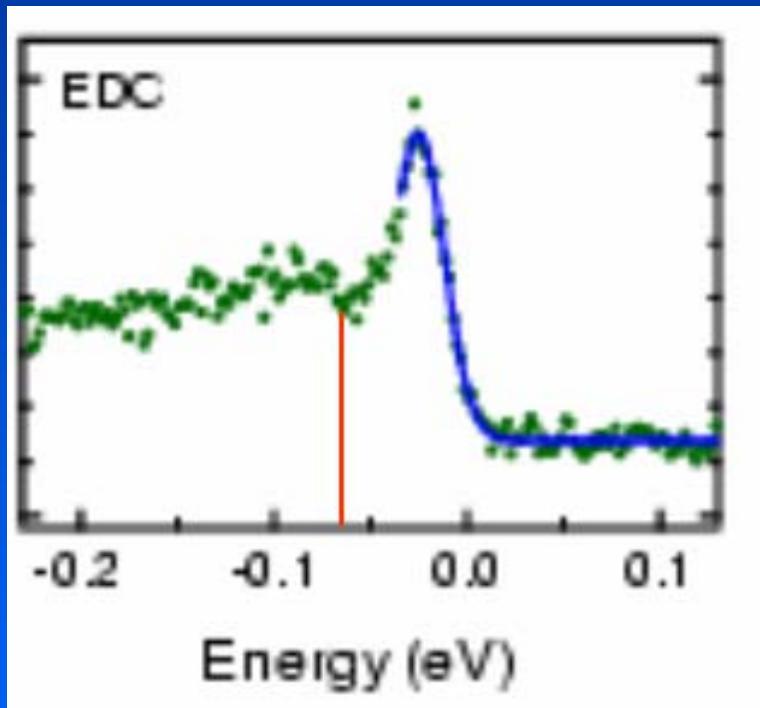
$$I(\omega, T, h\nu) \propto [(M_a(h\nu)A(\omega, \varepsilon_a, T) + M_b(h\nu) \times A(\omega, \varepsilon_b, T))f(\omega, T)] \otimes R_\omega + B(\omega, T)$$

Going from the anti-nodal to the nodal point (A band, $h\nu = 50$ eV)

The strength of the kink decreases

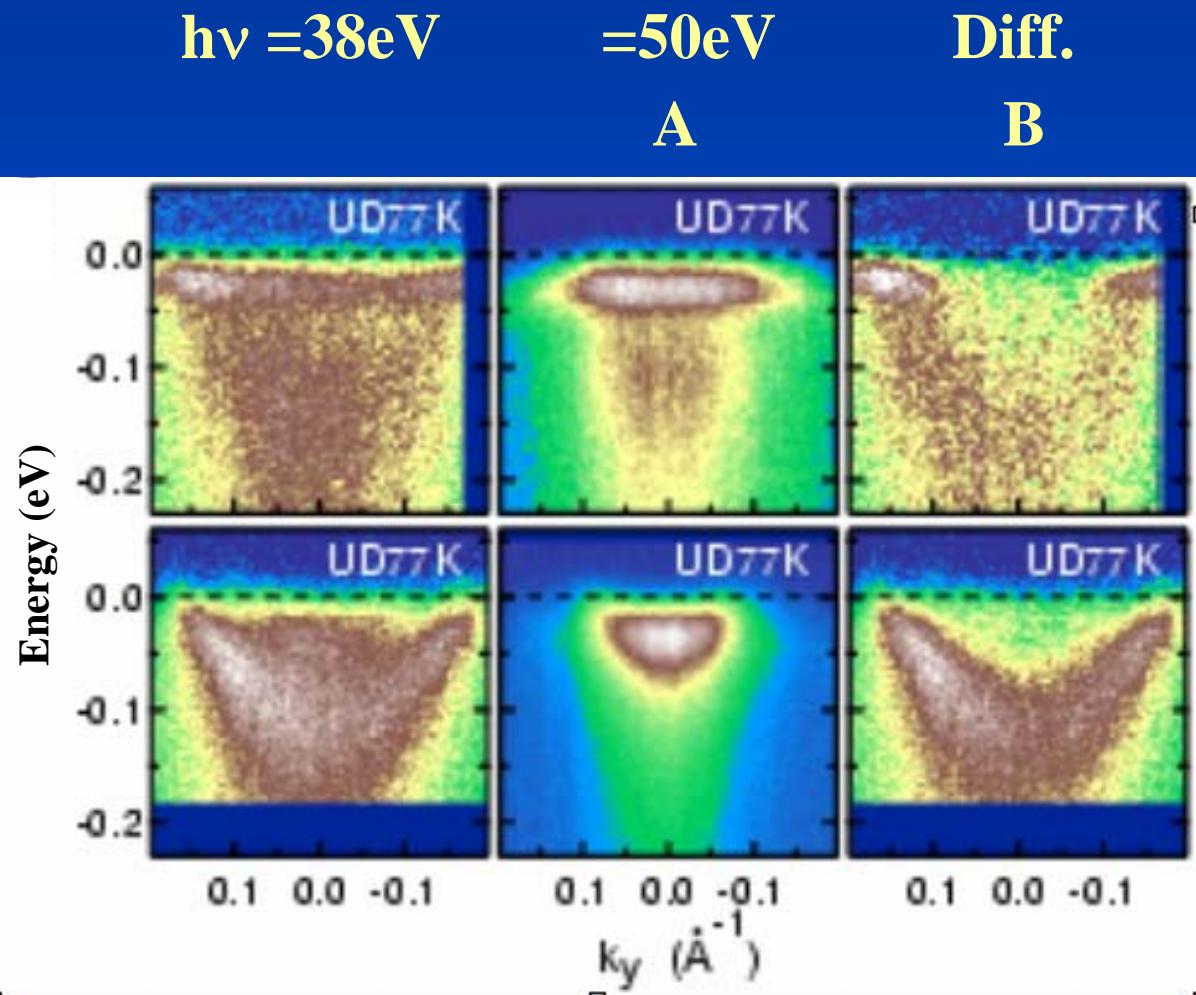


Pb/Bi2212 UD, B, EDC (const $k = k_F$)



Dip at 70 meV, $E_D = \Delta + \omega_0$
Coupling to a mode with
 $\omega_0 = 40$ meV

T-dependence of kink along $(\pi,0)$ - (π,π) , UD sample



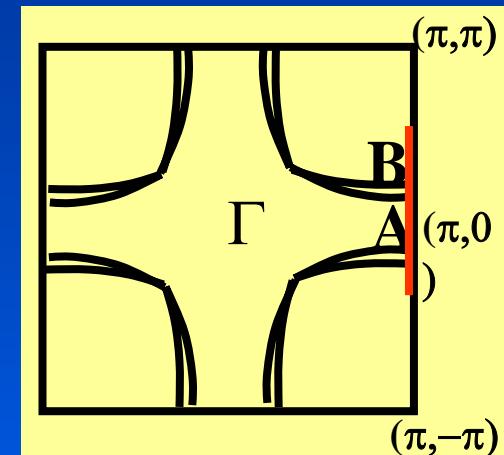
T =

30 K

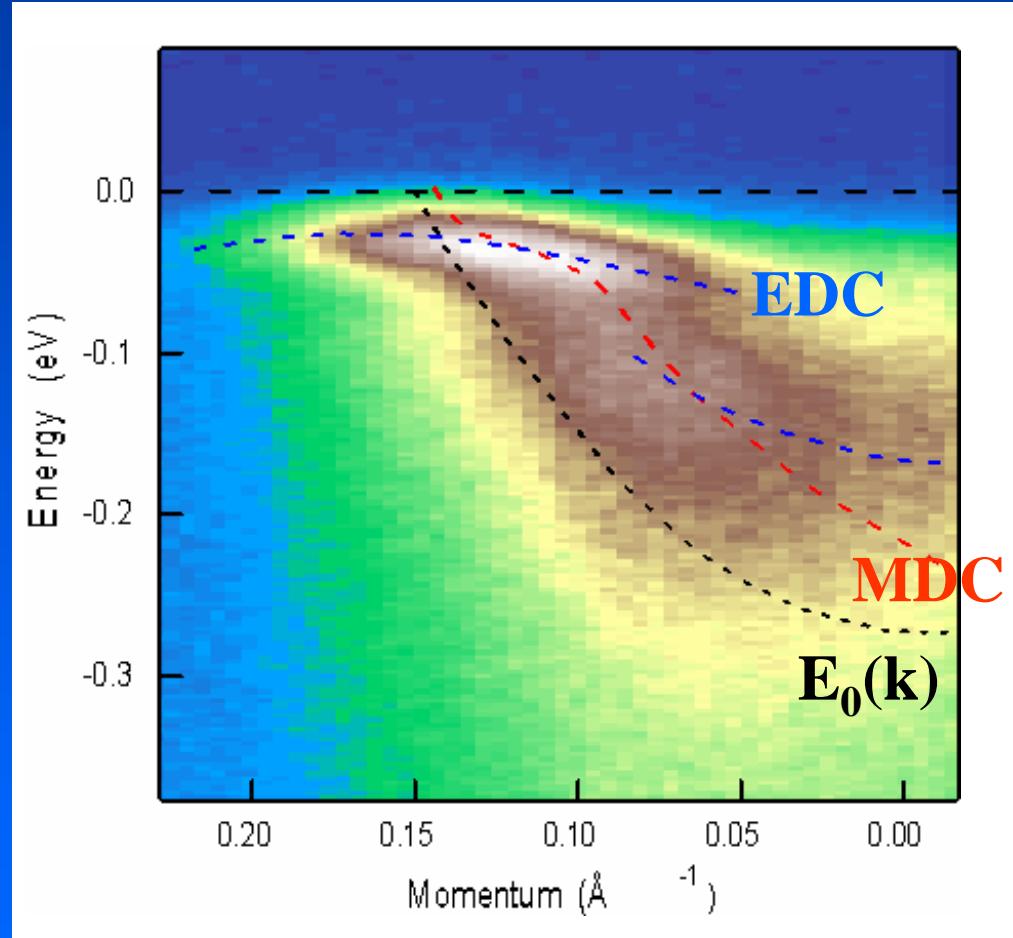
120 K

T = 120 K

Strong reduction of the coupling to the mode



Bi-2212 OP at the anti-nodal point (B)



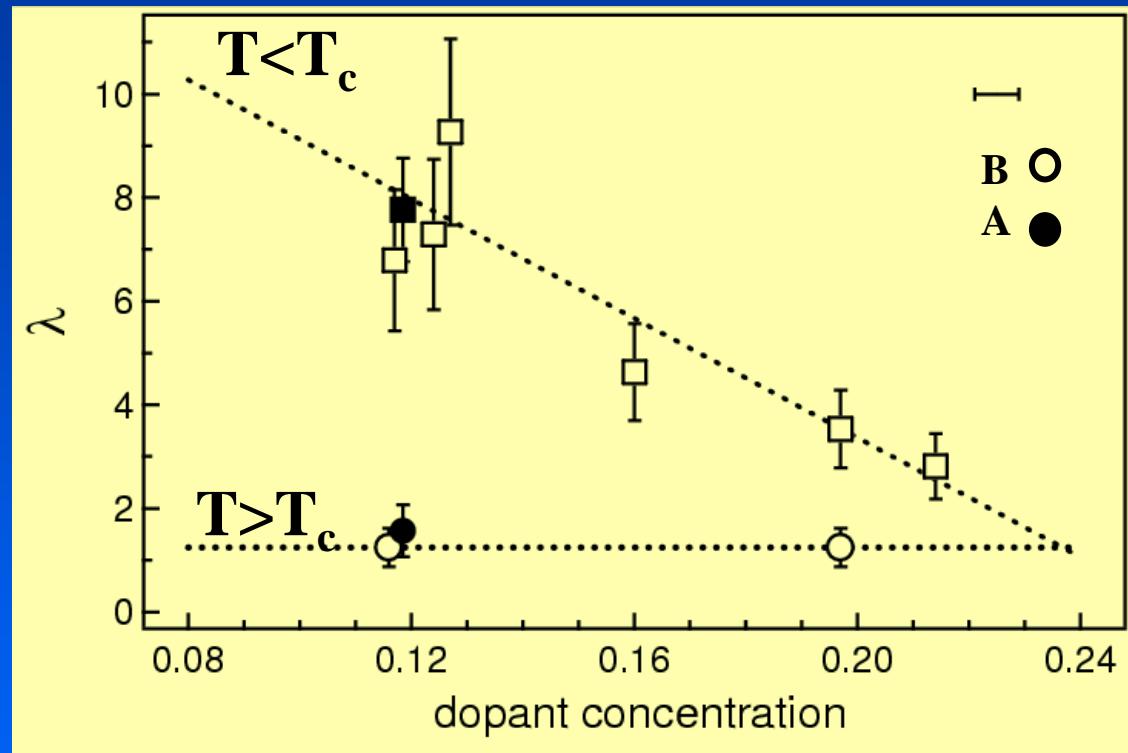
Evaluation in a model of
dressed quasiparticles

$$\varepsilon_{\mathbf{k}} = (E(\mathbf{k})^2 + \Delta^2)^{1/2}$$

$$E(\mathbf{k}) = E_0(\mathbf{k}) / (1 + \lambda)$$

$$\Rightarrow \lambda, m^*, \Delta$$

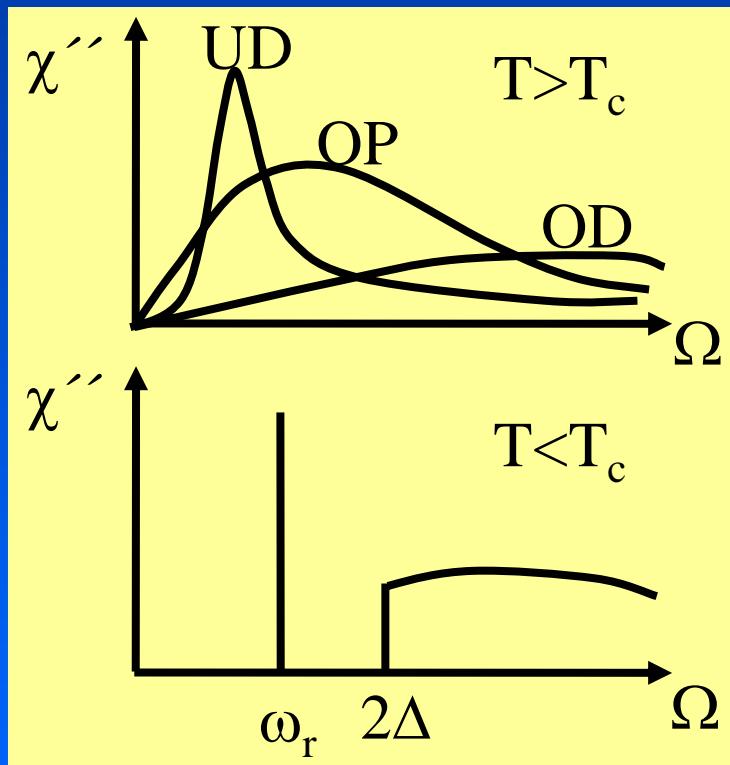
Pb/Bi2212, λ as a function of dopant concentration



In the UD region below T_c : very strong coupling to bosonic mode at ~ 40 meV.

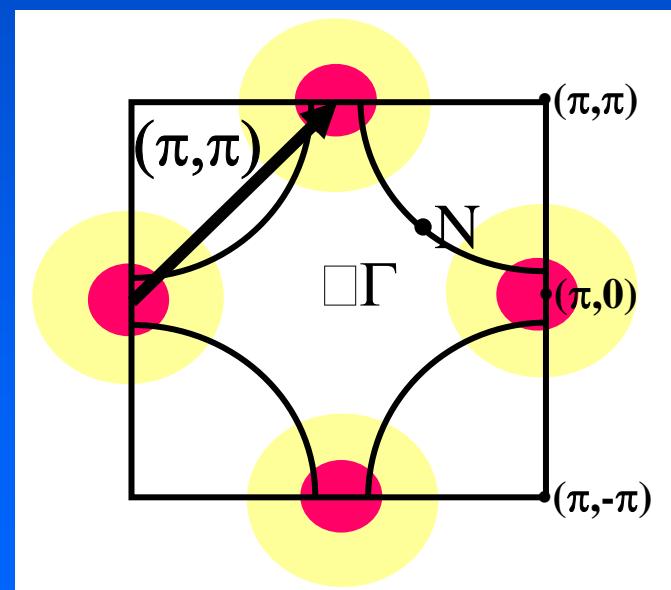
Above T_c : $\lambda \sim 1$, dispersive states for $E > \Delta$!.

Character of the mode??? Spin fluctuations or phonons



Spin fluctuations

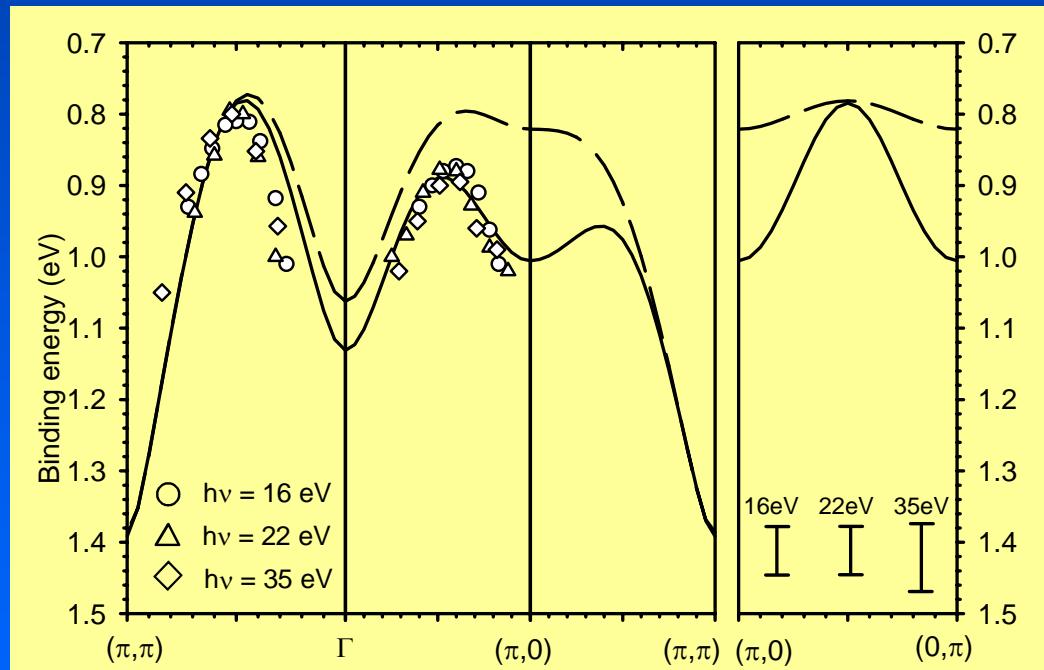
- energy (40 meV)
- q -dependence
- no coupling above T_c



Rossat-Mignot et al. P C 185, 86 (1991)
Mook et al. PRL 70, 3490 (1993)
Fong et al. PRL 75, 316 (1995)

Eschrig and Norman, PRL 85,3261(2000)
and PRL 89, 277005 (2002)

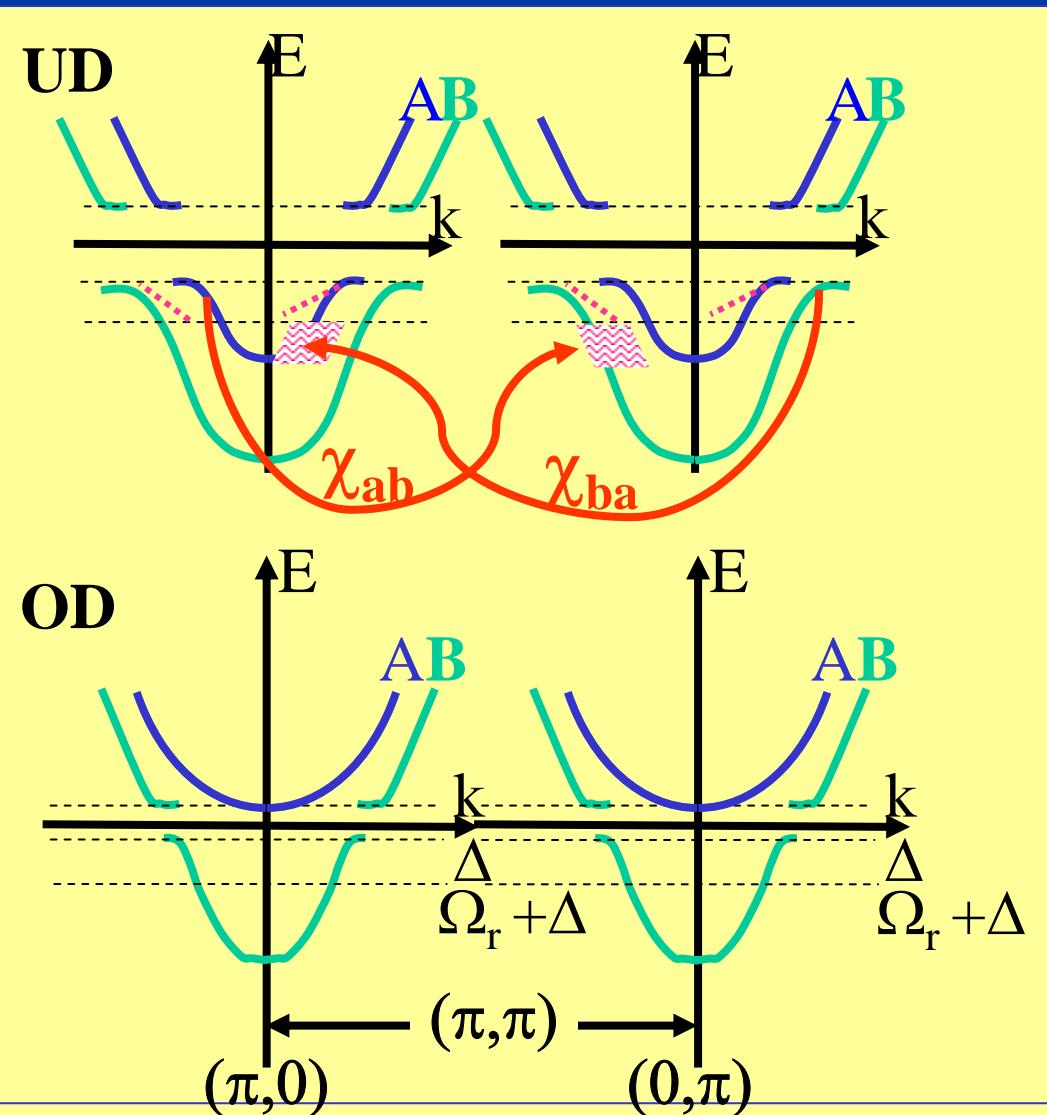
ARPES of $\text{Sr}_2\text{CuO}_2\text{Cl}_2$: the dispersion of a hole in an antiferromagnetic CuO_2 plane



From the width of the dispersion:
the dynamics of a hole
is not determined by
the hopping integral t
but by the exchange
integral J .

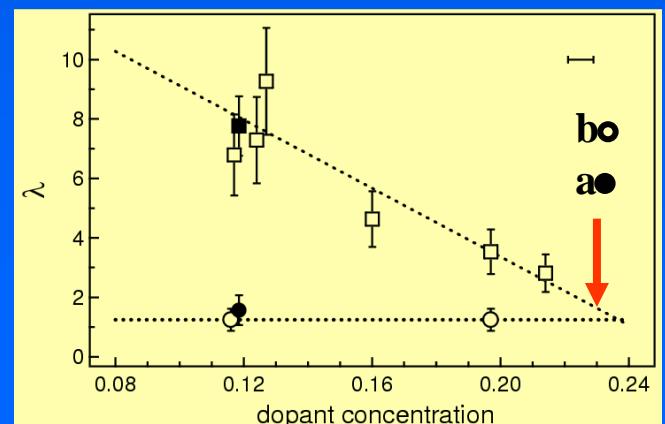
Strong interactions of
the electrons with the
antiferromagnetic spin
lattice of the Cu ions.

Coupling of a bilayer system to a resonance mode



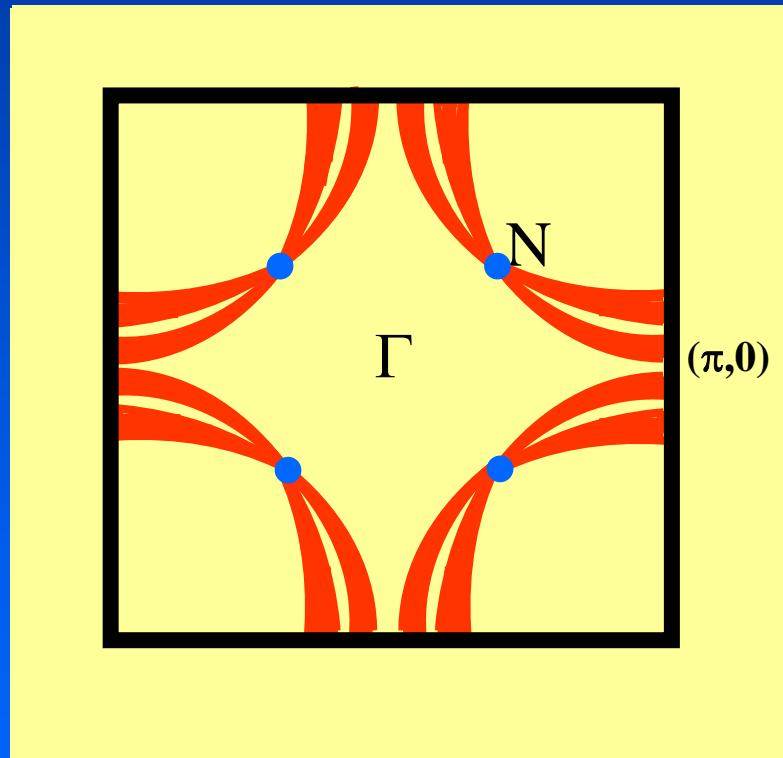
From neutron scattering:
the coupling via the
magnetic resonance mode
occurs only via the odd channel.
 $A \Rightarrow B$ or $B \Rightarrow A$
but not $A \Rightarrow A$ or $B \Rightarrow B$

AB and BA coupling not possible in the very OD case.
Coupling starts when A moves below E_F

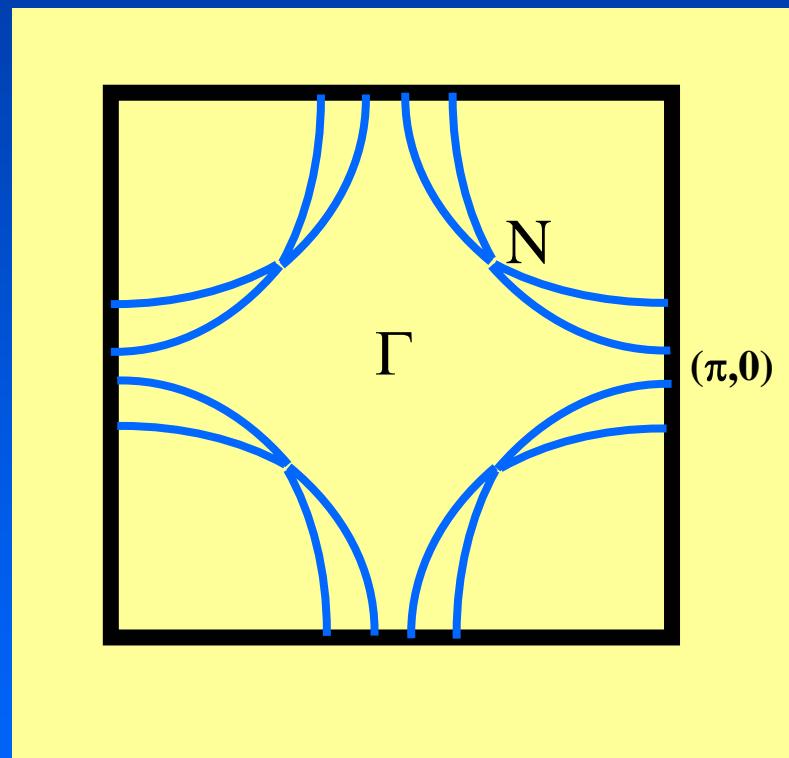


Summary - dressing of charge carriers in high- T_c superconductors

$T < T_c$



$E > \omega_R + \Delta, T > T_c$

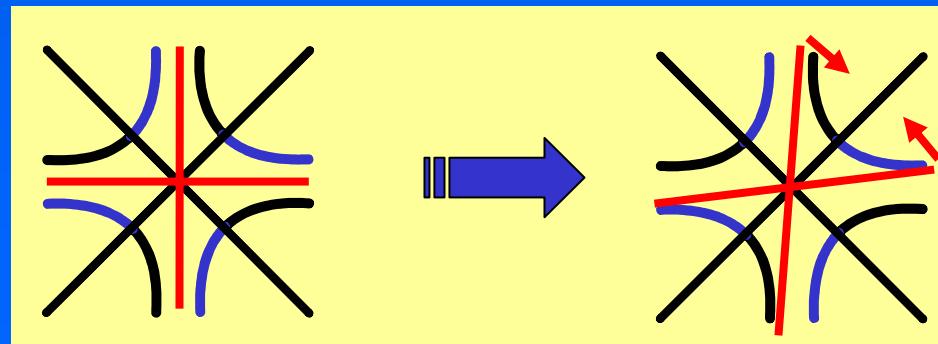
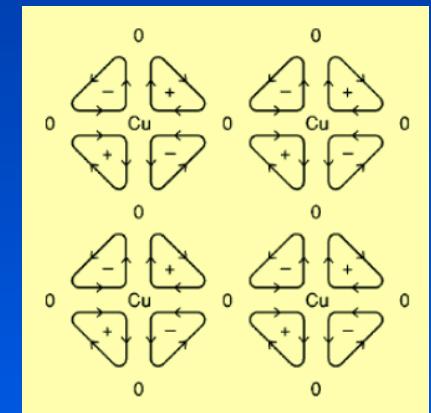


- Coupling to a (magnetic resonance?) mode at ~ 40 meV
- Coupling to a continuum (of spinfluctuations?) with $\lambda \sim 1$

Pseudogap range, new phase with circulating currents with time-reversal symmetry-breaking Quantum critical point at optimal T_c

C. M. Varma PRB 61, R3804 (2000)

Dichroic signal = difference between photocurrent for right and left circularly polarized photons. Should become non-zero in the Γ M-mirror plane. Pseudo-rotation of the mirror planes.



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7–137 (2000).
d spin system.

Spontaneous breaking of time-reversal symmetry in the pseudogap state of a high- T_c superconductor

A. Kaminski*†, S. Rosenkranz*†, H. M. Fretwell‡, J. C. Campuzano*†,
Z. Li§, H. Raffy§, W. G. Cullen†, H. You†, C. G. Olson||, C. M. Varma¶
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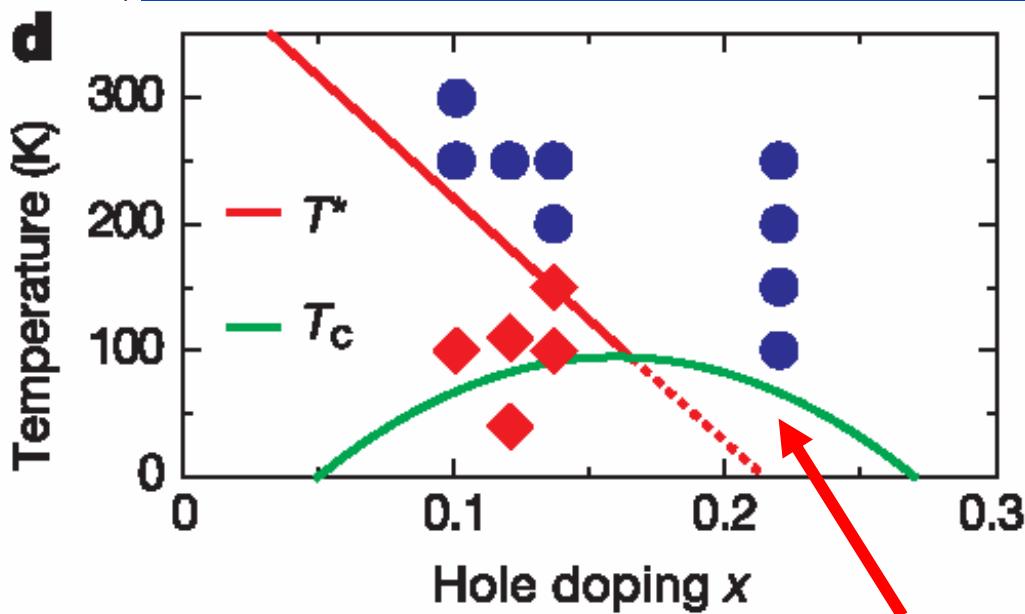
§ Laboratoire de Physique des Solides, Université Paris-Sud, 91405 O

|| Ames Laboratory, Iowa State University, Ames, Iowa 50011, USA

¶ Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07

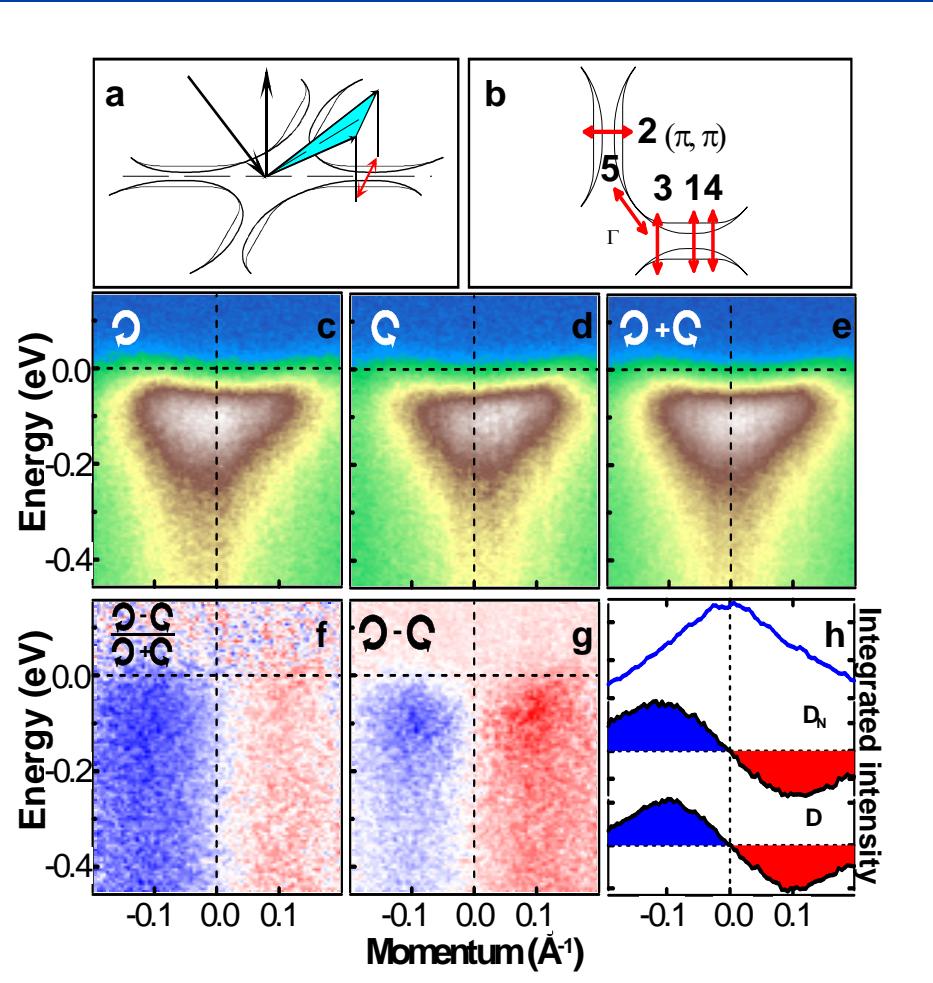
Synchrotron Radiation Center, Stoughton, Wisconsin 53589, USA

A change in ‘symmetry’ is often observed when matter undergoes a phase transition—the symmetry is said to be spontaneously broken. The transition made by underdoped high-temperature (high- T_c) superconductors is unusual, in that it is not a mean-field transition as seen in other superconductors. Rather, there is a region in the phase diagram above the normal-state electronic transition temperature T_c (where phase coherence and superconductivity begin) but below a characteristic temperature T^* where a ‘pseudogap’ appears in the spectrum of electronic excitations^{1,2}. It is therefore important to establish if



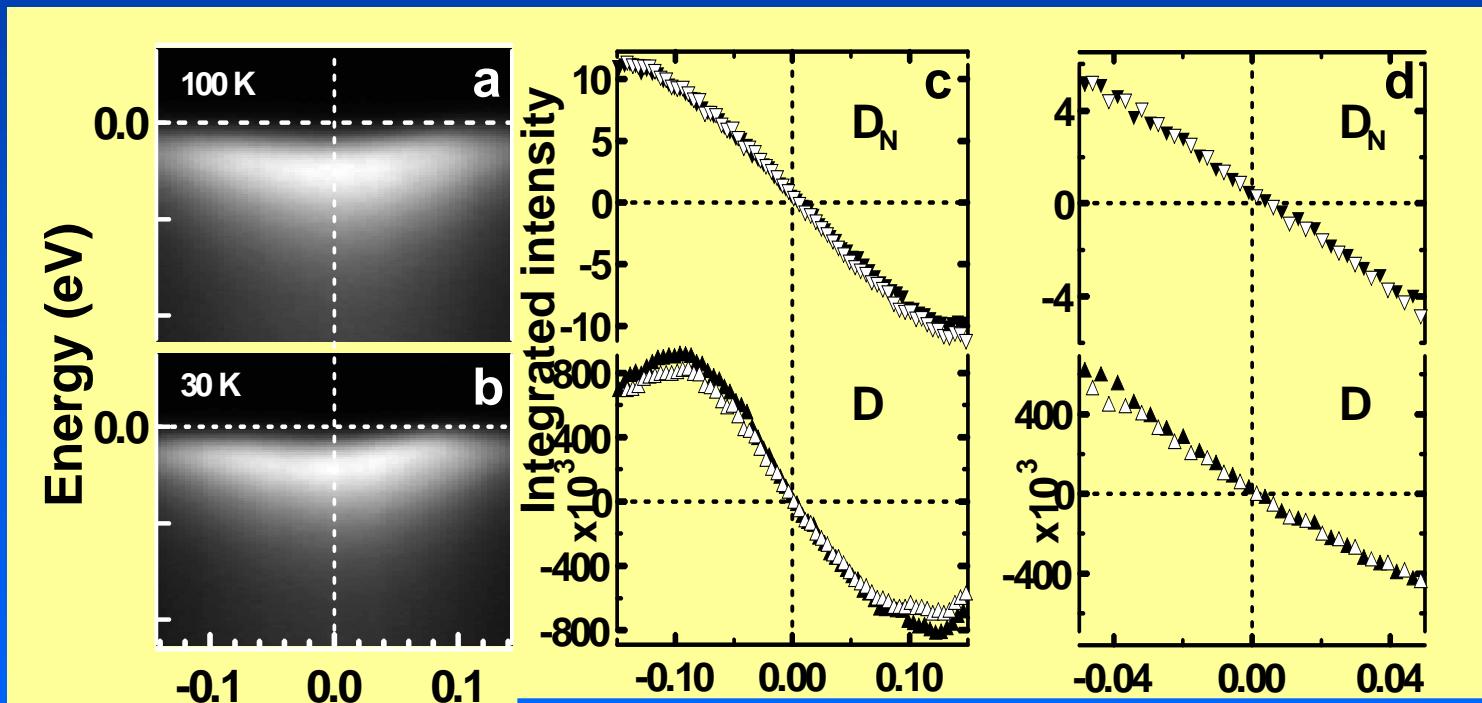
Circular dichroism in ARPES of superstructure-free $(\text{Bi},\text{Pb})_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

OD70K T= 300 K



Electromagnetic elliptical wiggler at ELETTRA
 $h\nu = 50 \text{ eV}$

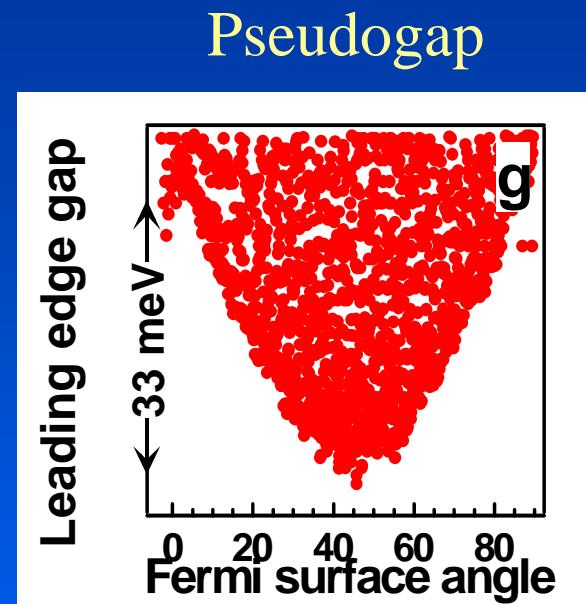
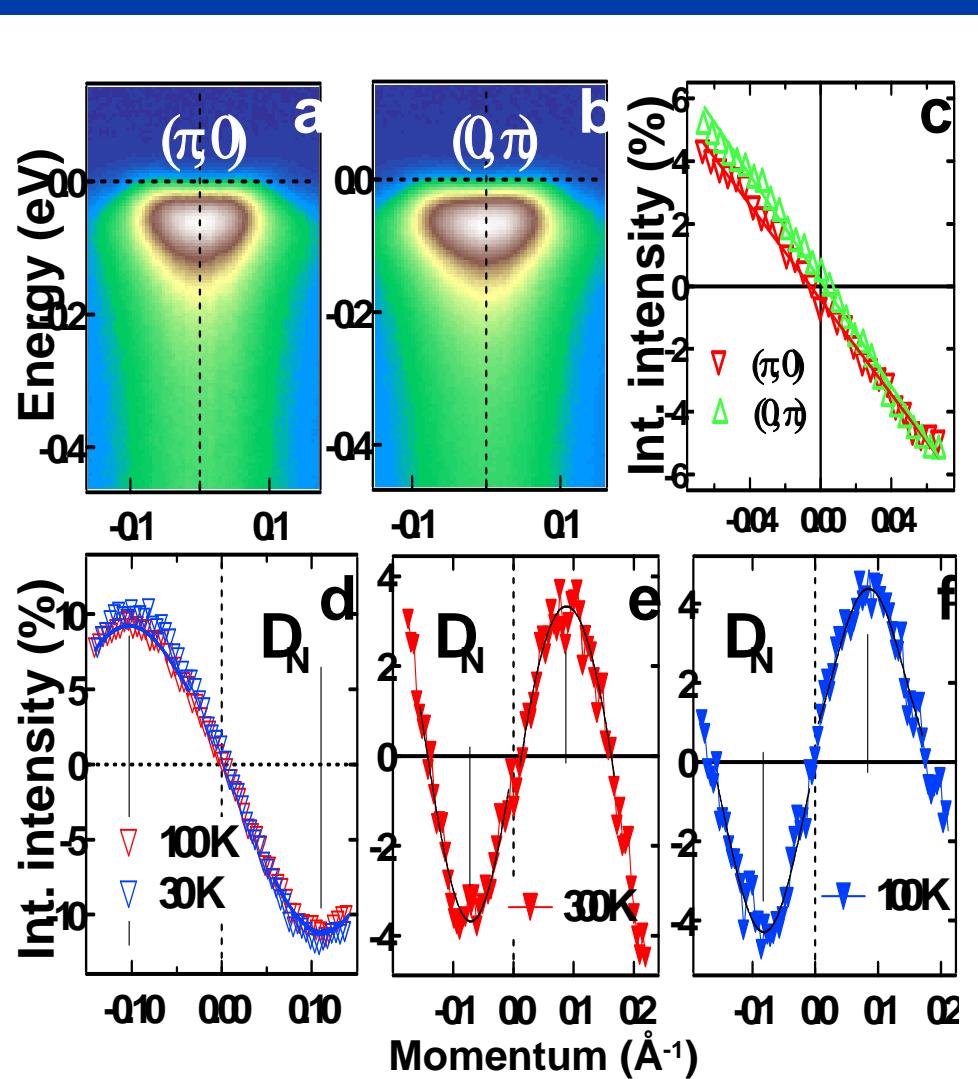
OD 77K sample



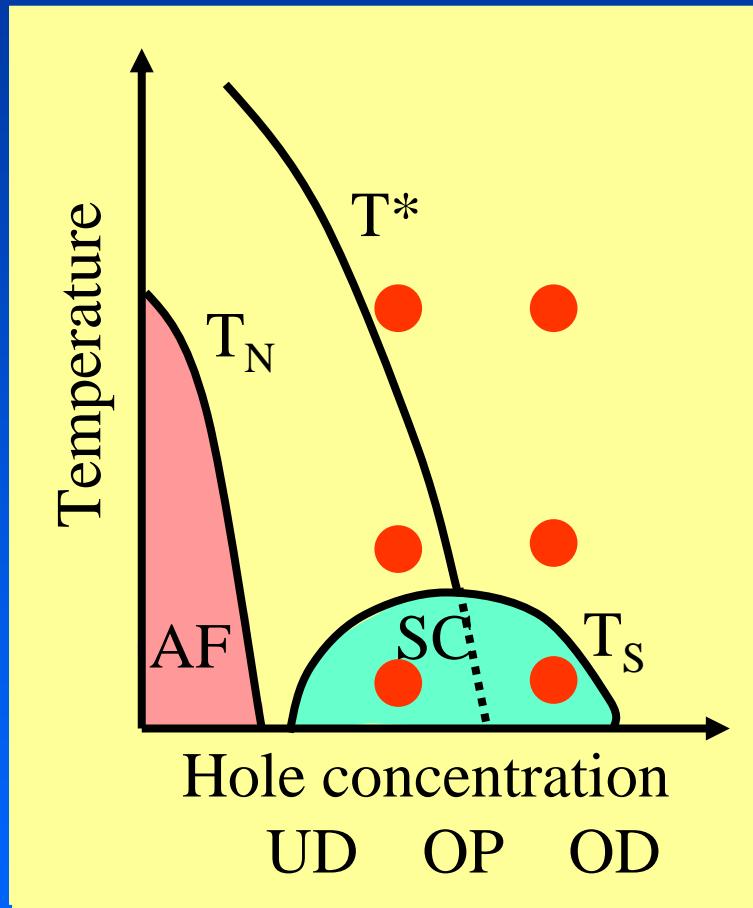
$T = 100\text{ K}$

$T = 30\text{ K}$

Pb-Bi2212 UD77K sample



Circular dichroism in Pb-Bi2212



Dichroic signal at the Γ - $(\pi,0)$ and Γ - (π,π) mirror planes $< 0.3 \%$ or the ‘pseudo-rotation’ of the mirror planes $< \pm 0.3^\circ$

Previous experiments on Bi2212 films observed a dichroic signal of 4 % at Γ - $(\pi,0)$ mirror plane or a ‘pseudo-rotation’ of 2.3°

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ELETTRA

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Konstantin Nenkov

IFW-Dresden